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Damage Analysis of Wire Rope From a 34-Month Ocean Mooring

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ABSTRACT

Damage analysis of samples from a 304 stainless steel rope was conducted to determine the extent and origin of damage mechanism defects and to measure their accumulated effect upon mooring line break strength. The rope was located in the upper portion of the NOMAD buoy mooring line and had been subjected to 34 months of continuous immersion in the Gulf of Mexico. The primary objective of this initial study was to supply corrective information leading towards an extension of service life,

Damage defects of mechanical and electrochemical origin were identified and located in the 1250-foot length of wire rope mooring. A study of these defects revealed a specific pattern of degradation. Dominant centers of damage were associated with a wire rope deformation-bend and with a "protective" neoprene jacket cover. In each case the initiating damage mechanism was identified as an abnormal mechanical motion which removed the protective coatings afforded by lubricant and cathodic protection. Subsequent corrosion of the stainless steel generated an abrasive sediment in the lubricant to promote a self-supporting degradation process. The wire rope retained 88% of its initial break strength. Elimination of the causes that initiated abnormal mechanical motion would increase this retained strength to 96%.

This study indicates the need to properly use post-service damage analysis in optimization of buoy system design. A complete understanding of usage effects in terms of failure/reliability will depend upon continued damage analysis during several prototype installations.

PROBLEM STATUS

This is a final report on this phase of the problem; work is continuing in other phases.

AUTHORIZATION

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INTRODUCTION

Object

The opportunity to conduct a damage analysis study upon a portion of a NOMAD mooring line--from a mooring recovered after 34 months in the ocean--presented itself during a period when moored buoy technology was being subjected to review. A significant part of this review of the design and engineering methods currently in use is the need for understanding failure mechanisms of wire rope often used in ocean moorings. The primary purpose here is to describe the procedures and results of an initial study of the mechanical damage to wire rope after 34 months in the Gulf of Mexico. As this study proceeded the scope was broadened somewhat to direct attention to greater possibilities for obtaining damage information when an overall program could be conducted. A concurrent study reported on corrosion effects to this wire rope (1).

Background

Before proceeding into a discussion of the damage studies it would be well to review briefly the conditions that exist today in moored buoy technology, in an effort to place damage analysis in its proper context.

Although moored buoy systems have been used for many years, the recent emphasis on ocean utilization has greatly increased interest in these marine structures. Such interest results from an expanded need for oceanographic and meteorological data, as well as from the desire to explore and work in the ocean and to monitor its physical properties. Not only is the number of potential buoy systems increased but the requirements for performance of such systems--including reliable life, predictable motions, dependable installation and retrieval, and acceptable costs--have become more stringent. Illustrative of these requirements are the specifications for the National Data Buoy System (2) and those of the Sea Spider installation (3). Once these specifications are reviewed and compared with previous requirements the full import of the new requirements is realized. Goals that include low initial cost, improved longevity in service and predictability of system response to the environment can be achieved only if comprehensive dynamic analytic techniques exist and are fully supported by good definition in all of the environmental and engineering parameters, including damage/failure mechanisms. Current knowledge is insufficient to meet this task; hence, research is required.

A current review of buoy technology has revealed the magnitude of the required research effort in pertinent areas. These areas include (a) analysis, to permit more accurate prediction of forces and motions in moored buoy systems, (b) environment, to better specify the forcing functions and ocean conditions, (c) engineering parameters, to more adequately prescribe hardware characteristics and properties, (d) operational procedures, to establish dependable at-sea techniques for installation and retrieval, and (e) damage analysis, to better understand the effects of usage in terms of failure/reliability. Information gathered by specialists in each of these areas (4-9) indicates that progress towards achievement of the optimum moored buoy design will be best served through a concurrent approach in the programming of research. While some of the areas will lend themselves to quasi-independent programs of laboratory research (development of dynamic analytic techniques, quantitative measure of hardware characteristics) others will deoend upon an influx of data gathered from initial prototype systems (measurement of environment parameters, development of damage analysis). A continuous program of prototype construction is important to insure proper validation of new developments as these occur in all pertinent areas of buoy technology.

An additional aspect of buoy system research was made evident as work progressed towards evaluation of damage in the NOMAD wire rope mooring. The in-sea mechanisms which produce damage and limit the life of the buoy system are of mechanical, electro-chemical and biological origin. Although separate study of these mechanisms through laboratory simulation and field experimentation has value, such study by itself can reveal neither the extent nor the rate of degradation that is produced when these mechanisms interact within the complex marine environment. As is shown in a later section of this report, the techniques employed during post-service damage analysis may be used for an evaluation of these cumulative effects. Also, the full worth of damage analysis cannot be realized unless it is supported by measurement of certain mechanical parameters of the system during the service period, i.e., some limited means for conduction of in situ research measurements should be included in specifications for the initial prototype systems.

To summarize briefly, the most expeditious program for optimization of buoy system design will utilize data from a growing volume of hydrospace research to improve the response of successive prototype systems. Specifications for these systems should include the means for (1) fulfillment of their utilitarian purpose, (2) validation of new research developments and (3) conduct of in situ research. Post-service damage analysis can assist materially in the necessary design and development process. If the scope of these damage studies is sufficiently broad they will supply feedback information essential to growth in the overall program.

Damage Analysis Studies

Mechanical, electrochemical and biological mechanisms combine to produce the accumulated damage found in a marine system. During damage analysis the characteristic defects for each mechanism are first identified, then located and measured to reveal specific patterns of system degradation. The manner in which dominant centers of damage relate to one another and interact within the system to produce overstressed components is of interest. Once sufficient clues have been gathered as to the history of events that produced change in the system, it may be possible to isolate the initiating mechanism and suggest new procedures for extension of system life. A detailed knowledge of system design parameters is essential throughout this process and will prevent a purely subjective conclusion.

The scope and objective of damage analysis became clear only as this initial study progressed and was paralleled with the effort to understand all of the problem areas in buoy technology. It is natural then that certain limitations in the current effort will appear: these will be noted in the text.

THE NOMAD BUOY SYSTEM

The particular NOMAD Buoy System considered here was an automatic weather station anchored in 11,250 feet of water at latitude 25-00N and longitude 90-00W in the Gulf of Mexico. This installation was under the cognizance of the Naval Weapons Quality Assurance Office, Meteorological Instrumentation Division, QAO-56. The general NOMAD system is shown in Fig. 1. The buoy had nominal dimensions of 20x10x8 feet, a displacement of 10 tons and a loaded draft of 7 feet. It was fabricated from 6061-T6 aluminum and was initially isolated from the mooring with phenolic insulators.

Several changes were incorporated in the particular system which was installed and is damage-analyzed in this report. Changes are underlined within the following sentences. A <u>1250-foot length</u> of 304 stainless steel wire rope of 0.75-inch diameter and 6x19 Warrington, independent wire-rope core, (IWRC) 7x7 construction was connected to the 15-foot length of stainless steel chain at the upper end of the composite moor line shown in Fig. 1. Connections were made to this chain and to the synthetic line at the lower end of the steel rope with appropriate stainless steel thimbles and cable clamps. Near the buoy an iron anode was fastened into the line just below the stainless steel chain by means of 0.75-inch stainless steel safety shackles. The anode was to provide cathodic protection for the stainless steel portions of the line. The lower end of the 0.75 inch stainless steel rope was covered with a single <u>250-foot length of neoprene jacket</u> of one-inch I.D.x1.25-inch O.D. The purpose of this cover was to provide protection against mechanical abrasion of the synthetic line in the

event that this line would rise towards the surface during periods of no tension in the mooring.

After incorporation of these changes the particular system under study was implanted and it provided 34 months of continuous service until recovery in April of 1969. The system had not failed, nor was there evidence of imminent failure.

INSPECTION OF THE MOORING SYSTEM

The recovered NOMAD Buoy System was made available for inspection at the Washington Navy Yard. It had been brought here for the purpose of post-installation analysis since its useful lifetime was one of the longest achieved at that time. Only the stainless steel portion of the mooring was analyzed in this study.

In initial discussions it was suggested that a corrosion analysis be conducted by the Metallurgy Division and a mechanical damage analysis by the Ocean Technology Division of NRL. The corrosion report (1) should be studied in conjunction with this report. Cross references are made where these are helpful. As work proceeded in mechanical damage analysis it quickly became apparent that mechanical effects due to corrosion were an integral part of this study and must be included.

Sampling Procedure

The only guidance available for choosing locations of samples for laboratory study was the external appearance of the rope; selections were made upon this basis. The appearance of the rope at the chosen locations is shown in the color photograph in Fig. 2. Prior to sample selection, the neoprene jacket was slit over its full length and removed to expose the covered portion of the steel rope to view.

Following the selection of locations, wire rope samples were cut from the mooring line. Seven groups of adjacent 2-, 4-, and 10-foot lengths were removed from the mooring. The 2-foot lengths were used for corrosion analysis (1) and the immediately adjacent 4-foot lengths were used for damage analysis. It was from these 4-foot samples that the final specimens of 30-, 12-, and 3.5-inch lengths were obtained; these were used to provide break-strength, damage-catalog and lubricant-study data. The 10-foot samples are shown by number in Fig. 2 and the adjacent 4-foot samples are identified as to position in the rope in Columns 1 and 2 of Table I. The 10-foot samples were held in reserve for possible later use in damage analysis. For example, when need for additional information on the condition of the rope nearer to the vertical center of the jacketed portion developed, a 4-foot specimen (6a) was cut from the appropriate 10-foot sample.

Table I - NOMAD Damage Analysis Summary

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Specimen No.	Distance from Upper End of Wire Rope	Special Features	Test Break Strength		Numbers of Damage Points*									Sedimentation Sediment/ Lubricant	
			Load (lb)	Percent below Nominal (%)	Outer Strands					IWRC				Outer Strands	IWRC
					M	S	B	C	T	M	Br	C	T	%	%
1	13'-17'		47,800	3.6	13		None	10						33	21
2	98'6"-102'6"		43,100	3.0			None	14						39	27
3	519'4"-523'4"	Rope Bend	47,400	4.4			None	90		58		35		41	28
4	1000'7"-1004'7"	1000'	47,600	4.0			None	15				10		27	32
5	1010'7"-1014'7"	Neoprene Jacket	44,750	9.8	75	35	None	180	18	130	17	110		51	57
6	1090'8"-1094'8"		48,000	3.2			None			10		28		20	25
6a	1103'8"-1107'8"		47,700	4.0			None					30		27	20
7	1227'5"-1231'5"	1250'	43,650	12.0	124	40	None	204	3	101	4	52	3	29	33

*LEGEND

Note: All specimens contained both mechanical and corrosion damage in light form; this is not included here.

Damage Categories:

Mechanical - M - Medium wiremarks (Less than 5 omitted)
S - Medium and heavy scrapes (All counted)
Br - Complete wire breaks (All counted)

Corrosion - C - Medium and heavy etches, pits and striations (Less than 5 omitted)
T - Tunnels in wires (All counted)

Specimen Appearance

The external appearance of the wire rope is important and merits discussion. Samples 1 through 7 in Fig. 2 will be used to illustrate rope appearance at various locations along the mooring. The 10-foot samples shown in this photograph are identical in appearance to the adjacent 4-foot specimens except that a bend was contained in specimen 3 (519'4" to 523'4")* which is not shown in samples 3 of the photograph.

The upper 104.5 feet of the rope contained a whitish deposit (samples 1 and 2). Analysis indicated that this deposit derived from two sources. First, microscopic examination revealed a presence of both fibrous and crystalline structures. The fibers were not identified but some of the crystalline structures had the appearance of algae (silicious diatoms). This portion of the deposit is commonly known as marl and results from marine life decay. Second, the Metallurgy Division had conducted both X-ray diffraction and spectrographic analyses of the surface products of the rope. Reference (1) notes that when a metal is cathodically protected in sea water under certain conditions of temperature and electric potential, the protected metal will develop white calcareous deposits (calcium and magnesium salts) on its surface. The presence of $CaCO_3$ (calcite) as a major constituent of these deposits is reported down to the 13-foot position and as a minor constituent down to a distance of 104.5 feet. The spectrographic analysis also indicated very strong lines for calcium, magnesium and silicon and strong lines for aluminum at the 11- to 13-foot distance. Reference (1) concludes that the presence of aluminum and calcite in the near-buoy portion of the wire rope indicates that the rope was not only being cathodically protected by the iron anode, $\gamma FeO(OH)$ was present, but also was receiving cathodic protection from the aluminum buoy. The aluminum buoy probably was not electrically isolated from the mooring for at least a portion of the service period.

The mechanical condition of specimen 3 (which is not shown in sample 3 of Fig. 2) should be noted. Specimen 3 contained the permanent bend that is illustrated by the sketch in Fig. 3. The bend is shown in its relaxed condition. This permanent deformation showed no wire breaks nor great external disarrangement of strands or strand wires. The bent cable was included in the 30-inch specimen removed for break-strength test. Its presence introduced certain variations in the damage data which will be discussed in a later section of the report.

The appearance of the wire rope from approximately 100 feet to 1000 feet is shown by samples 3 and 4, Fig. 2. There was an excellent

* These lengths refer to distances along the stainless steel rope, measured from the buoy end of the rope.

retention of rope lubricant which imparted the dark green-to-black discoloration. It is important to note the similar appearance of sample 6, located approximately 1100 feet from the upper end of the rope, and therefore 100 feet below the upper end of the 250-foot neoprene jacket. It will be shown later that this portion of the rope (near sample 6) was in excellent mechanical condition and was similar to samples 1, 2 and 4 in this regard.

The heavily rusted appearance of samples 5 and 7 is generally indicative of the condition found in the wire rope which lay beneath and near both ends of the jacket cover. The rust did serve to indicate the two most heavily damaged locations in the wire rope as is later described.

In general the external mechanical condition of the rope was excellent. Once samples were cleared of surface lubricant and deposits, wires and strands appeared free of any great amount of corrosion. Some external scrape marks were visible to the naked eye on samples 5 and 7; the significance of these is discussed later.

WIRE ROPE BREAK STRENGTH

Test Procedure

In conducting wire rope break strength tests certain precautions regarding procedure are important. Relative displacement of wire and strands during cutting, terminating and testing is to be avoided. There must also be a near-perfect axial alignment of terminators and rope; the spelter socket seems to offer the best opportunity for minimizing stress disturbances in the free length of rope near its terminators. In theory, as the test machine begins to apply load, the stress distribution in wires of the rope cross section should be exactly that produced by service load in the center cross section of an infinitely long rope. This condition is necessary if accurate and consistently reliable break strength values are to be obtained. In practice this condition is achieved, or nearly so, if at final rupture all strand breaks have occurred simultaneously and within the free test rope length. Considering the complexity of the procedure one generally accepts any test in which three to four strands of a six-strand rope rupture simultaneously and all ruptures occur within the free length.

Additional allowance must be made during test of used cable where non-uniform strand damage can produce non-uniform discrepancies in strengths of individual strands. For all break strength tests on the NOMAD cable, ruptures of two or more strands occurred simultaneously within the free rope length.

Rope break strength tests were conducted in a 60,000-lb Tinius Olsen test facility having a calibrated accuracy of better than 0.8%. The accuracy of the break strength values of the mooring line given in column 4 of Table I are considered to be within 1% of the actual strength of the rope, for the locations shown in column 2. The maximum free test-length for rope specimens as determined by cross-head clearance in this machine was 26 inches. All NOMAD break-strength tests were conducted with specimens having this free length.

Pre-Service Break Strength

In attempting to compute the per cent reduction in strength, considerable difficulty arose as to the proper selection of a base value to represent the pre-service strength of the rope. Unfortunately no rope samples had been tested prior to installation. The following reasoning was employed to determine pre-service break strength. The manufacturer guarantees that for any given contract a specific rope will produce either nominal, or better than nominal, break strength. Because the manufacturing set-up process is expensive and because there remain certain uncertainties even for the best engineering technique available, the manufacturer always sets up for a break strength in excess of nominal. Uncertainties in wire rope manufacture would include the allowed tolerance in single-wire mechanical properties, approximations necessary to the engineering design procedure and variations introduced by the equipment during the production run. In selecting his desired break strength, the rope engineer is faced with two factors which contribute to reliability in manufacture. First, there is a percentage variability estimate of his own past engineering capability in translating initial variables into a given break strength goal and second, there is the estimate of what the break strength variability will be over the long length of completed rope. For the sake of this argument, two percentage factors of minimum value were assumed after discussion with a number of rope engineers. Since both of these are $\pm$ 3%, it becomes obvious that the pre-manufacture design break-strength-goal should be the nominal strength plus 6%, and the user may receive a finished product having a break strength up to 6% over the guaranteed nominal value. However from a user standpoint, the guaranteed nominal break strength should be assumed as the working design parameter since he cannot afford to destructively test the entire mooring line before use.* The nominal strength of the 0.75-inch, 6x19 (IWRC 7x7) stainless steel (304) wire rope used in this system was given as 49,600 lbs.

* This statement is not intended to preclude strength tests on mooring lines prior to service. Such tests should always be conducted on samples taken from locations immediately adjacent to both ends of the proposed service length of rope. There is no better way of assuring manufacturers adherence to guarantee.

With these points in mind, for the NOMAD damage analysis, the nominal break strength, i.e., purchase-contract guarantee, was used as the base in computing the percent reduction in rope strength due to damage during service. With manufacturers profit in the balance there is a high degree of probability that the initial rope strength was no lower than the guaranteed nominal strength and therefore the computed percent reduction in strength is a minimum and is related to the minimum strength that initially could occur anywhere in the rope mooring.

THE DAMAGE CATALOG

Break strength values provide a measure of the total effect of accumulated damage in a given length of rope. Because damage defects reduce the effective metallic cross-sectional area of the rope, they effect a reduction in its break strength. Thus, large reductions in break strength help to locate the incidence of major damage areas along the moor line. However break strength studies are of little help in identifying, locating and measuring the different damage mechanism defects that produce these accumulated effects. For this purpose one must dismantle the rope and microscopically examine a given length of each wire in the construction. Since there were 163 wires in the rope cross section (Fig. 4), and a total of eight specimens for examination, some organization of the effort appeared necessary and this was supplied by the "damage catalog".

The method of labeling the wires in a cross-section of the rope is shown in Fig. 4. Outer strands were numbered successively 1-6 and the wires in each strand were labeled alphabetically. The same procedure is used for the independent wire rope core with the prefix of 7 added for additional identification. The diameters of undamaged wires were measured in numerous locations and the averages are listed in Fig. 4.

The damage catalog identifies the mechanism producing the defect observed in a wire. One sheet from the 48-sheet NOMAD damage catalog is included as Table II to illustrate the format. Note three of the major column headings in Table II which are labeled INTERstrand Wire Marks, INTRAstrand Wire Marks and Wire Breaks. These columns identify mechanically induced defects. In a fourth major column corrosion defects are entered and are classified in the sub-columns headed Etches, Pits, Striations and Tunnels. The fifth major column indicates when photographs of the individual wires were obtained to show damage. The meaning of the mechanical damage symbols is shown at the foot of the chart. Corrosion damage extent conforms in symbol definition to that employed for mechanical damage, i.e. etches, pits and striations of Light extent would exhibit a wire penetration of up to 0.001-inch depth, Medium extent from 0.001-inch to 0.003-inch depth and Heavy extent from 0.003-inch to 0.005-inch depth.

Table II - Damage Catalog Format Qualitative Procedure for Identifying & Locating Damage Mechanisms

NOMAD 6x19-7x7 IWRC 304 SS - Location, 1014 ft. 7 in. - 1024 ft. 7 in. Sample Length 12.25 in.

Damage** / Wire No.*	INTERstrand Wire Marks Caused by									INTRAstrand Wire Marks				Wire Breaks Distance From End (in)	Corrosion												Photos Ident. (Reel, section, Photo. no.)
	Adjacent Outer Strand			Adjacent IWRC Strand			Central IWRC Strand								Etches			Pits			Striations			Tunnels			
	L	M	H	L	M	H	L	M	H	B	L	M	H		L	M	H	L	M	H	L	M	H	L	M	H	
7-1-A		x		x	x			x			x			3/4	x			x	x			x					15/3/2,3,4
B		x		x	x		x				x				x			x	x	x		x					
C	x	x	x		x		x				x				x					x		x					15/3/5
D		x	x		x	x		x			x				x					x		x					15/3/6
E	x	x			x			x			x				x					x		x					
F	x	x			x			x			x				x			x	x	x	x						
G											x			1,8	x				x	x							15/3/7
7-2-A		x			x			x			x				x			x	x	x	x						
B		x			x		x	x			x				x			x	x		x						
C	x	x		x	x		x				x				x			x	x	x	x						
D	x	x		x	x		x					x			x			x	x		x						
E	x	x		x	x		x	x				x			x	x				x	x						
F	x				x			x				x			x	x			x	x							
G											x			4,9,11													
7-3-A		x			x			x			x			9		x			x	x							15/4/4
B		x			x		x				x					x			x	x	x						
C		x			x		x	x			x				x	x			x			x					
D		x			x			x				x			x	x			x	x	x						
E	x	x		x	x			x				x			x	x		x	x		x						
F		x		x	x		x	x				x			x	x			x	x	x						
G											x			9	x				x		x	x					16/2/9
7-4-A	x	x		x				x				x			x				x	x	x						
B		x		x				x				x			x				x	x	x						
C		x		x	x			x				x			x			x	x		x						
D		x		x	x		x	x				x			x	x		x	x	x	x						
E		x		x	x			x				x			x	x			x		x						
F		x			x			x				x			x				x	x	x						
G												x		4,6	x			x			x						

*See Figure 4 for wire nomenclature

**Mechanical Damage Extent

B-Burnish marks-Of extremely light depth

L-Light marks- To 0.001 in. depth

M-Medium Marks-From 0.001 in. - 0.003 in. depth

H-Heavy Marks-From 0.003 in. - 0.005 in. depth

Some difficulty was encountered in establishing an optimum specimen length. A specimen length of 12.25 inches was selected because trial runs on specimens cut from the extra 10-foot lengths of rope showed that shorter specimen lengths results in a significant loss of wire-break counts. This specimen length of 12.25 inches includes more than two strand lays and therefore generously covers all possible combined stress patterns in the wires of the rope.

A similar difficulty was encountered with selection of the numbers of strands to be counted. It was not possible to determine when a count was representative of damage if only a few strands were examined; it therefore became necessary to count all strands in each specimen.

After establishing the catalog format, locating and defining damage defects, and fixing upon a consistent work routine the very time-consuming task of filling out the damage catalog for the eight specimens was completed. With respect to the eighth specimen, which is numbered 6a in the analysis summary, Table I, it should be recalled that this additional sample was taken from the 10-foot sample at this location when the surprising results for specimen 6 were revealed. This specimen (6a) provided information at a position which was a little closer to the mid-length location of the neoprene jacket; as noted in Table I it verifies the previous data from specimen 6 for this location.

Definition of Damage

Two kinds of photographs are available to help the reader in forming an opinion as to the nature of NOMAD wire rope damage. These are photographs of the rope cross section and the more detailed photographs of individual defects.

Figure 5 shows a cross section of the rope which is closely representative of the internal conditions found in specimens 1, 2, 3, 6 and 6a (see Table I). There is only slight evidence of mechanical wear and abrasion and corrosive etching. No very severe damage is evident.

In a similar manner Fig. 4 reveals damage that is indicative of conditions in specimens 5 and 7, and to a much lesser degree in specimen 3. The mechanisms causing these defects are identified and located in Table III. In addition to the defects shown in Table III, clean sharp wire breaks occurred typically at positions 7-1-A, 7-2-G and 7-7-G in Fig. 4; these breaks were observed only in specimens 5 and 7 (see Table I).

Greatly enlarged views of mechanical and corrosion defects are shown in Figs. 6, 7 and 8. Only the most severe defects are shown and these were predominantly located either at and adjacent to the rope bend (520' 7" down from the upper end of the rope) or in those sections

Table III

Identification of Mechanisms Causing Defects*

Mechanism	Labeling of Examples
a) External Scrape	3 - C
b) Interstrand Wire Mark Due to Adjacent Outerstrand	1 - G
c) Interstrand Wire Mark Due to IWRC	5 - A, 7 - 1 - C, 7 - 4 - A
d) Intrastrand Wire Marks	1 - H, 5 - M, 5 - R, 7 - 1 - E
e) Corrosion Etches	7 - 7 - G, 7 - 7 - C
f) Corrosion Pits	5 - N
g) Corrosion Striations	7 - 3 - G
h) Corrosion Tunnels	Heavy 5 - I, Medium 1 - E, Light 4 - I

* Note - Table identifies mechanisms that produce defects in Fig. 4.

of the rope located just inside the open ends of the neoprene jacket (1010'7" to 1014'7" and 1227'5" to 1231'5").

Summary of Damage Data

After the damage count was completed for all wires in the eight specimens, a means of summarizing the data in a form that would reveal dominant centers of damage was sought. The solution to this problem will be found in the Nomad Damage Analysis Summary of Table I in columns titled Damage Peaks. This condensation of damage catalog data was obtained by first summing all defects of like extent for the outer strands and for the IWRC and then eliminating all defects that fell below an arbitrary standard in magnitude. Thus only defects in the medium and heavy class are retained and these are summed in columns 6 through 14 of Table I. The summary illustrates in numberical form the location of damage peaks along the mooring line, (vertical traverse of columns). Or, if one selects a given position in the mooring line and scans the data horizontally, a display of the different types of mechanism defects is available with numerical indication of the frequency of their occurrence.

LUBRICANT STUDY

As the study progressed, the important role of the rope lubricant became evident. After 34 months of exposure at sea, the wire rope mooring retained a large amount of lubricant over most of its length. An excellent quality and quantity of retained lubricant was always associated with the low damage area of the mooring cable.

Curiosity about the role of the lubricant in protecting the rope against mechanical and corrosion damage led to a weight and a spectrographical analysis of lubricant samples taken from the outer strands and from the IWRC at each specimen location. Data from the weight analysis is contained in columns 15 and 16 of Table I under the heading, Sedimentation. The entries represent the percent weight of sediment per unit weight of lubricant. An increase in the sediment content of the lubricant samples is generally associated with an increase in the extent of corrosion (columns 9 and 13 of Table I) as one moves from specimen to specimen down the mooring cable. This relationship fails at specimen 7. One would expect the sediment content for specimen 7 to be nearly that of specimen 5. The reason for this difference is not known.

A spectrochemical analysis report of lubricant samples taken from the outer strands and from the IWRC at each specimen location was obtained. There was interest in the relative distribution of corrosion products within the rope and along the length of the mooring.

The results did not indicate a difference between samples taken from the outer strands and from the IWRC.

The analysis indicated the spectral density of elements associated with cathodic protection of the stainless steel rope (calcium and magnesium) as compared to the spectral density of elements derived from its corrosion (iron and chromium) when these element-groups were viewed with respect to their occurrence over the full length of the wire rope moor. Very strong lines for calcium and strong lines for magnesium were shown in all lubricant samples taken from the outer strands of specimens located in the uppermost 1000 feet of the wire rope mooring. The analysis shows that cathodic protection afforded by the iron anode extended over the upper 1000 feet of the wire rope moor but appeared to terminate abruptly at the upper end of the neoprene jacket (1000 feet from the top of the rope). Of the elements associated with corrosion, strong to very strong lines for iron first appeared at the 520 foot level, very strong lines appeared for chromium at the 1000-foot level, and these indications prevailed from the points noted to the lower extremity of the rope. It is to be noted that elements associated with both cathodic protection and corrosion appeared at a distance of 520 feet down from the top of the rope, but this was also the location of the permanent bend in the rope. It was the presence of this mechanical deformation which produced corrosion in an otherwise protected section of the mooring. This effect will be discussed with some detail in a later section.

The results of the spectrochemical analysis were not sufficiently quantitative to establish the locations of damage peaks that were identified in specimens 3, 5 and 7 in Table I. They reflect instead upon the small degree of corrosion that occurred over the length of the mooring. These qualitative results are influenced by the relative magnitudes of the constituents in each sample.

DISCUSSION

Work was directed towards the placement of analysis data in a form to permit ease of interpretation. Reduction and summarization of data is contained in the NOMAD Damage Analysis Summary, Table I. Before proceeding with a correlation of these damage clues it is helpful to study the geometry of the NOMAD moored buoy system and to review the forces and motions that can exist in this system. Since not all of the design parameters of the system were available, this discussion is limited in some extent to information taken from the description of the general NOMAD system shown in Fig. 1. For the sake of brevity only obvious facts, directly related to the damage interpretation study, will be mentioned.

Throughout these preliminary discussions, and in the interpretative effort to follow, attention is directed to the presence of a design feature, the neoprene jacket, and to an installation or in-service mishap, the permanent bend in the rope.

Forces and Motions in the NOMAD System

Reference is made to the drawing of the general NOMAD System in Fig. 1. It is important to obtain some idea of the size and geometry of this system. If instructions on the drawing are followed to obtain the length of the composite line from buoy to anchor, this length (23,000 feet) will be found to approximate twice the depth of the installation (11,250 feet). Thus if the mooring line could be straightened by forcing the buoy to a maximum far-left position, it would assume a minimum angle of 30^o with the surface of the sea. In practice this condition cannot be reached because of the gravitational forces which act upon the massive components near the extremities of the line.

The curvature of the line when subjected to buoy load is actually quite complex. Each portion of the line -- wire rope, dacron, polypropylene and chain -- will assume a curvature in response to the force components (tension in the line -- gravitational force due to the wet mass of the line), and in accordance with its length (hydrodynamic forces neglected). The curvature will be greatest for the wire rope and chain sections, minimal for the dacron line (density 1.4) and essentially zero for the polypropylene line (density 0.92). Inflection points in the overall mooring will exist at each junction of dissimilar materials. An added inflection point will exist in the wire rope at the upper end of the neoprene jacket because of the added mass and the stiffening effect of this jacket. The angles formed by adjacent portions of the mooring at these inflection points are important. Under variable load these angles will change and there will be transverse motions in the moor line.

The sketches in Fig. 9 approximate the geometric shapes of the composite mooring line for two boundary load conditions on the buoy. For the first condition, a minimum horizontal force is applied to the buoy. The wire rope (approximately 1000 feet) hangs in a near vertical position and joins the dacron portion of the moor at a junction angle somewhat larger than 120 degrees. The dacron and polypropylene portions of the moor extend downward at an angle that approaches 30^o. The stainless steel chains and ballast ball lie on the sea bed. For the second boundary condition, a maximum horizontal force is applied to the buoy. The wire rope rotates to assume a more in-line position with the remainder of the moor. There is relatively smaller change in the angular position of the synthetic portions of the line, but an increased length because of added tension. The stainless steel chains and ballast ball may lift off the sea bed. Thus energy added from the buoy forces is absorbed within the mooring system through an angular deflection of the wire rope, an extension of the mooring line components and a lifting of the chain and ballast ball. Maximum extensions occur in the highly elastic synthetic portions of the mooring. The system is highly damped with respect to dynamic excitation of the buoy.

An interesting point can be made about the safety factor and the allowable design tensile force on the rope. In Fig. 1, a minimum break strength of 14,000 lb is specified for the dacron line. Assuming a safety factor of three, the allowable tension in this line, and an approximation to the tension in the lower end of the wire rope that was attached to it was 4670 lb. This tensile force in the wire rope might be increased by the weight of the 1000 feet of line ($\sim$1000 lb) to some 5700 lb at the upper end of the rope; thus, the minimum design safety factor for the wire rope was about 9. The allowable static stresses in the wire rope were low, a fact which contributed to the long life of the installation.

Correlation of Clues

The summary in Table I provides a tabulation of damage analysis data. For discussion purposes, locations along the wire rope mooring as noted in column 2 will be referred to by use of the specimen location number in column 1. Damage clues are listed below with pertinent comments as needed.

a) A permanent bend in the rope occurred at location 3, and is described in Fig. 3.

b) A neoprene jacket of 250-foot length covered the lower extremity of the 1250-foot wire rope, i.e., from location 4 through 7.

c) The break strength at each of the eight locations is shown in column 4 of Table I. A significantly low break strength value is indicative of a major damage area in the wire rope.

d) The percent reduction in break strength, below the nominal break strength of 49,600 lb, is given for each location in column 5. This data provides the minimum values of strength reduction in each case. Large reductions in strength are associated with major damage areas in the rope.

Damage peak data from the damage catalog for outer strands and IWRC are listed in columns 6 through 14. The numbers indicate the frequency of occurrence for the particular defect in a 12.25-inch specimen. Only medium and heavy defects are included in order to accentuate damage peaks. The following clues seem pertinent.

e) Mechanical defects in the form of wire marks (W), external rope scrape marks (S) and complete wire breaks (B) are listed in columns 6, 7, 8 for the outer strands and columns 11 and 12 for the IWRC. (No external rope scrapes could occur in the IWRC). Large numbers indicate major damage areas in the wire rope.

f) Corrosion defects in the form of etches, pits and striations (C) and tunnel defects (T) are listed in columns 9, 10 and 13, 14. Large numbers indicate major damage areas in the wire rope.

g) The percentage by weight of sediment associated with each per unit weight of lubricant is given for both outer strands and IWRC at each location in columns 15 and 16. Large percentages of sediment are associated with major damage areas in the rope.

Additional clues which could not be fitted into Table I are listed below.

h) The external appearance of the rope was of importance with respect to the incidence of rust in the lubricant which appeared in rope sections that lay beneath the neoprene jacket, but relatively near the open ends of this cover (locations 5 and 7 in Table I). The lubricant at these two locations was of very poor quality, with evidence that it contained considerable rust. It possessed little of the adhesive and cohesive properties of the lubricant evident in all other portions of the mooring. It was granular in structure and the particles it contained (later determined to be corrosion products) were abrasive as revealed by a scratch test.

i) The iron anode, mounted just above the top of the wire rope, had been placed there to provide cathodic protection for the mooring line. Spectrochemical analysis of lubricant samples indicated a degree of cathodic protection in the upper 1000 feet of the wire rope, locations 1 through 4. This protection did not extend to the wire rope inside the neoprene jacket.

It should now be possible to correlate these clues and to reconstruct events which led to a build-up of damage centers in the rope moor. Alternate vertical and horizontal traverse of the data in columns and rows of Table I provides a direct identification of the peak damage centers in the mooring line. These damage centers are obviously located at the rope bend (location 3) and under the upper and lower ends of the neoprene jacket (locations 5 and 7). Damage associated with the rope bend is small compared to damage at the other two centers.

History of Events

The origin of the permanent bend deformation in the wire rope is not known. Three possible explanations present themselves for consider-

ation; one may be quickly eliminated. The possibilities of occurrence (a) during recovery, (b) during the service period or (c) during the installation are to be examined in turn. First, occurrence during recovery of the mooring system from the sea is highly improbable, because a period of service in the sea was necessary to provide time for generation of the major mechanical and corrosion defects shown for location 3 in Table I. Second, occurrence during the service period is possible. A sudden release in load, e.g., when the buoy drops off the crest of a high amplitude wave, produces an abnormal condition in the rates at which stored energy are released in the wire rope. Stored tensile energy can be released at a faster rate than the stored torsional energy with the result that a loop or bight is formed in the line. Subsequent loading will tighten the loop, i.e., reduce its diameter, and if the loop does not release in time a permanent bend deformation, or in a worse case, a kink will be produced in the line. The time of occurrence of this event during the service period is not known, if this did occur at all. If the rate of damage formation could be established, the time of occurrence could be determined. Finally, since a time of occurrence during the service period can not be established it is possible that the bend was present throughout this period, i.e., it occurred during installation of the system. The manner of occurrence during installation would depend upon the particular procedures used and since this information is not available further discussion would be futile.

The events which produce a growth in damage defects after occurrence of a bend deformation seem fairly obvious. When a rope is permanently deformed the strands and wires within the construction are disarranged from their normal lay position. Subsequent cycles of load produce abnormal relative motion and excessive abrasive wear in unfavorably oriented wires. Abrasion removes the protective coating that forms on the surface of stainless steel when it is cathodically protected, and it also scrapes the surface clean of its protective lubricant. The exposed stainless steel provides new corrosion sites and corrosive defects will begin to appear. Corrosion products are added to the lubricant and since these are abrasive they convert the lubricant into (literally) a grinding compound. Thus an initial deformation bend produces an undesirable mechanical motion and resultant mechanical abrasion clears the way for corrosion. From then on these damage mechanisms are mutually supportive and the processes producing degradation are accelerated.

The events leading to production of the heavy damage centers just inside the neoprene jacket mouths are not so easily reconstructed. Note in column 7 of Table I the presence of medium to heavy scrape marks in the outer wires of the rope. Note, too, the absence of scrape marks for specimens 6 and 6a which are located near the length center of the jacket. These scrape marks (see Fig. 6A) must have been produced by relative axial-motion (rubbing) between jacket and rope. The rope is in the mooring load train but the jacket is not. Under cyclic load

the rope must move in and out of the jacket and there is indication (location of external wire scrapes) that this relative motion was large near the jacket ends but very small near the jacket center. The possibility of such relative motion did not at first appear admissable. After all, with one-quarter inch of clearance available between jacket and rope one could expect the jacket to remain seated on the lower rope clamps. Yet, the damage evidence could not be denied. Qualitative study of the forces and motions in the buoy system helped to remove these doubts. It is to be observed from this discussion and from the sketch in Fig. 9, that the reseating of the jacket on the lower rope clamps is most likely to occur only for a condition of zero rope tension. With the first inception of load the wire rope (1250 feet) assumes an angular deflection from the vertical and forms a catenary curvature. With increasing load the jacketed portion of the rope approaches an angle of 30^{o} to the horizontal plane. Internal frictional forces between jacket and rope engendered by rope-jacket curvature and by transverse support of the jacket by the rope prevent any uniform motion of the whole jacket over the rope. In effect the rope under cyclic load apparently moves in and out of both ends of the jacket with little or no relative motion near the length center of the jacket. The amount of rope extension at each end of the jacket when a tensile load of 4000 pounds is applied equals 1.60 inches. (The elastic modulus of the rope was 14,000,000 psi and its metallic cross-sectional area was equal to 0.268 square inches.)

The scrape marks are indicative of but one mode of the jacket - rope motional environment which in its totality precipitated damage in the rope. As stated in the previous discussion on forces and motions in the NOMAD system, inflection points in the curvature of the composite mooring line will occur at the junction of dissimilar line components and at the upper end of the neoprene jacket. Thus inflection points existed at both ends of the jacketed portion of the rope and under changing load conditions transverse motions of the line also developed at these points. As previously noted any action which cleaned the surface of the stainless steel of its protective coating and of its lubricant would initiate corrosion damage sites and promote a mutually supportive chain of degrading events. The listing of damage defects in Table I for these two damage centers (locations 5 and 7) is proof positive of the potency of this mechanical effect.

Extension of Service Life

A solution to the jacket and the rope bend-deformation problem are paramount to an extension of service life for the NOMAD System. It has been shown that mechanical mechanisms were responsible for initiation of the degradation processes at damage centers in the wire rope portion of the NOMAD mooring line; that these mechanisms were generated through a mishap either during installation of the system or during its service

period, or again through the design addition of a "protective" neoprene jacket over the lower portion of the moor. It should be noted that neither cathodic protection nor the protection afforded by the lubricant was effective in preventing the growth of subsequent corrosion and mechanical defects in the presence of the initiating mechanical mechanism. In the absence of this mechanism, i.e., at the length-center of the neoprene jacket, the lubricant itself was sufficient to inhibit corrosion.

It is the prerogative of the designer to make changes in his system and he will no doubt look to (1) more corrosive-resistive materials for his wire rope, (2) the possibility of a close fitting extruded jacket over the entire length of the wire rope with bonding to the end terminations or (3) complete removal of the jacket with an increase in the density of the adjoining moor line component to negate need for this appendage, and finally (4) a careful log of installation, service and recovery procedures to institute corrections in these areas as they appear necessary.

Prediction of Failure/Reliability

It should be noted first that this damage analysis was restricted to the wire rope portion of the composite mooring and therefore any discussion of system life or reliability must be limited to this area. With this restriction in mind, it may be observed that after 34 months at sea this NOMAD wire rope mooring retained 88% of its initial strength. If corrections are made to eliminate the generation of damage peaks in the mooring, the remaining ultimate strength for the same period of service, and under like environmental conditions, would be increased to 96%. It would probably be safe under these conditions to predict a service life of at least five to six years for this portion of the system; however, such predictions will remain hazardous until the normal rate of degradation with respect to known service conditions can be determined. Information or data from this damage analysis study is limited to a single data point on the reliability curve, and even this tiny bit of information can not be validated with a quantitative description of the environment and engineering parameters that produced it.

CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this initial study was to supply certain corrective information to the designer of the NOMAD system through damage analysis of the wire rope portion of its mooring. Evaluation and criticism of the procedures employed during the study were included in the text.

The conclusions of the report may be itemized as follows:

1. The wire rope portion of the NOMAD mooring retained 88% of its initial strength after 34 months at sea. With removal of the causative factors that initiated the principal damage centers in the mooring, this retained strength would be increased to 96%.

2. Elimination of mooring damage centers would appreciably extend the service life of this wire rope component. An exact prediction is dependent upon a determination of the rate of degradation in the mooring.

3. The generation of major damage centers resulted from two causes, first, the presence of a wire rope deformation-bend which originated through mishap during the installation or in-service periods and second, the addition of a "protective" neoprene jacket cover that was drawn over the lower end of the wire rope during system construction.

4. In each case the initiating damage mechanism was identified as an abnormal mechanical motion which removed the protective coatings afforded by lubricant and cathodic protection. Subsequent corrosion of the stainless steel generated abrasive sediment in the lubricant to promote a self-supporting degradation process.

5. This initial study definitely indicates the large amount of interpretive design-analysis information which can be obtained from careful damage analysis procedures.

Certain recommendations are made in regard to the supply of supportive information prior to the conduct of future studies in the hope that these recommendations will speed future damage analysis, increase their efficiency and reduce the subjective nature of the interpretative result.

1) Fifty-foot samples from either end of the mooring line should be obtained prior to construction of the system. These samples would be used for laboratory evaluations of the initial, pre-service characteristics of the mooring line.

2) Specifications of the final as-constructed system, with all essential design parameters, should be supplied to the damage analyst.

3) A log of installation and recovery procedures, with special note made of any mishaps which occurred during these operations, is needed.

4) A tensiometer and inclinometer should be inserted in the moor line adjoining its uppermost extremity. Telemetered data from these instruments would do much towards creation of a mechanical reference for damage rate data.

These recommendations also pertain to the need for a broadening of the scope of the damage analysis study. The true worth of the analysis can be realized only if it is included as an integral part of the program for optimization of buoy system design and is supported with detailed information from all related areas.

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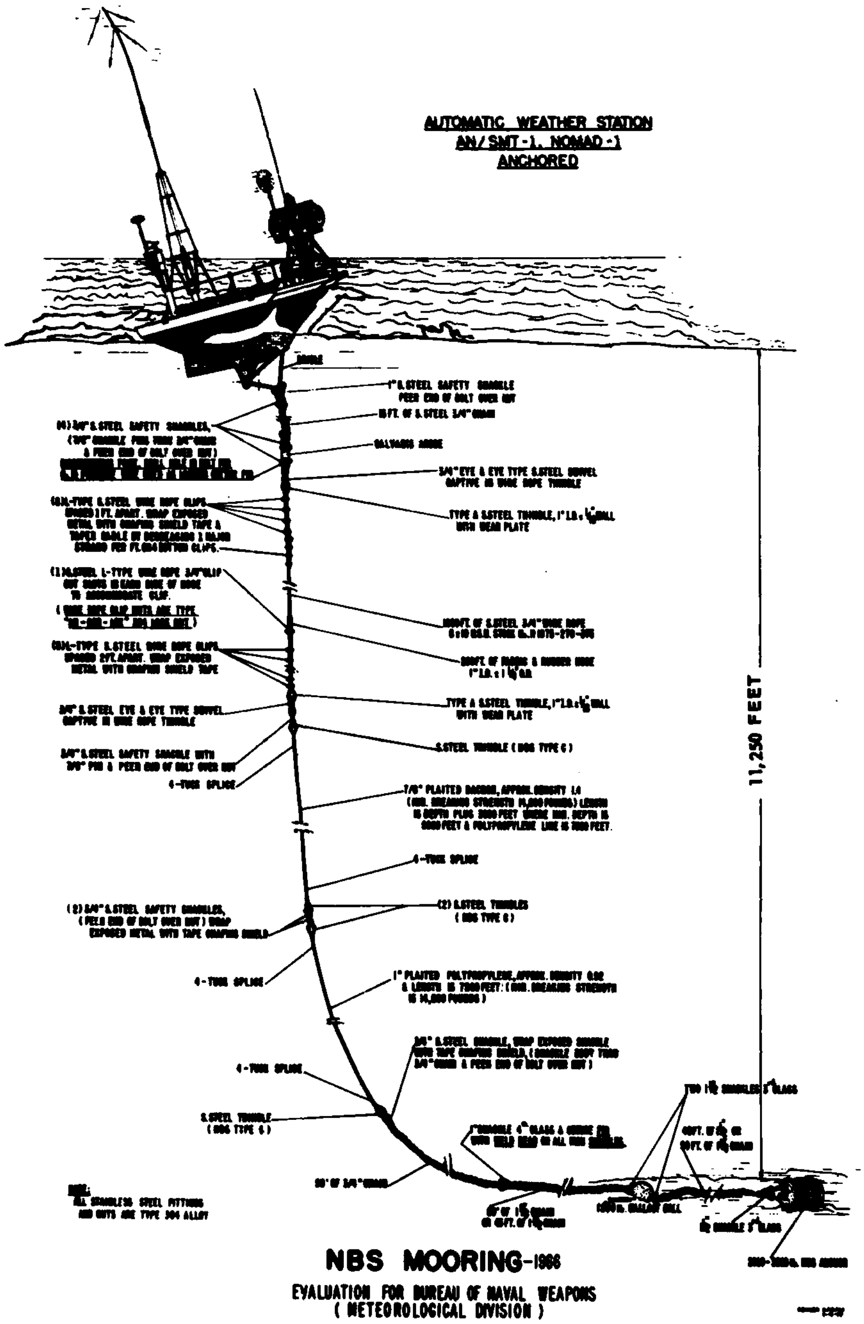

Fig. 1 - The General NOMAD System. Several design changes were incorporated in the system which is analyzed in this report. Changes are noted on page 3.

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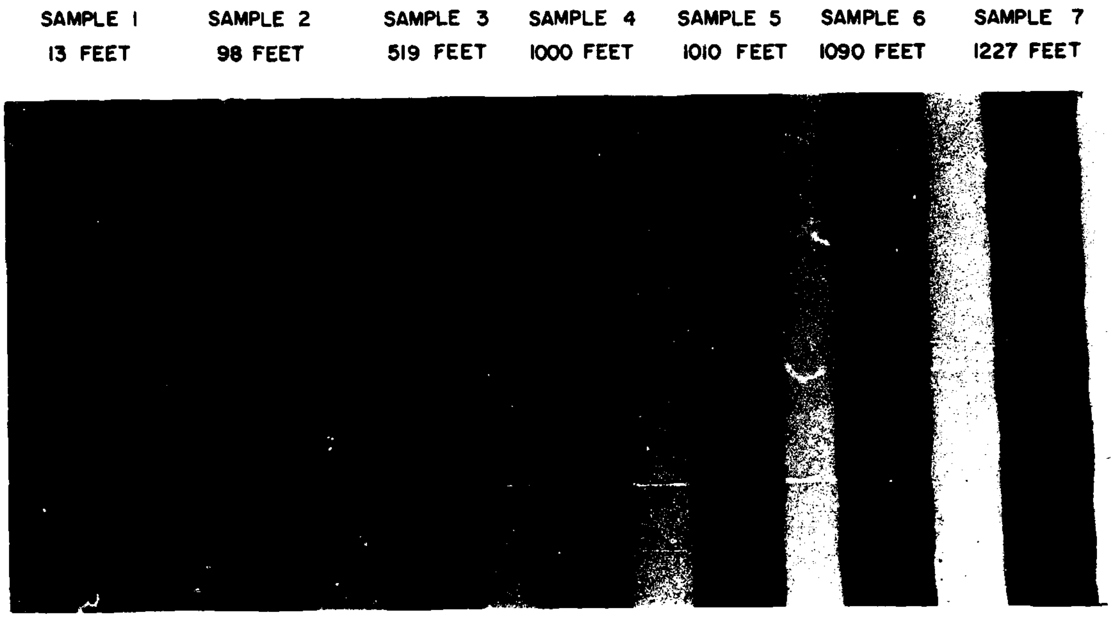


Fig. 2 - Appearance Of Wire Rope Mooring Samples. The external coloration of wire rope deposits provided a first rough indicator of the internal condition of the wire rope. Numbers and distances identify each sample and indicate their approximate location with respect to the buoy end of the mooring.

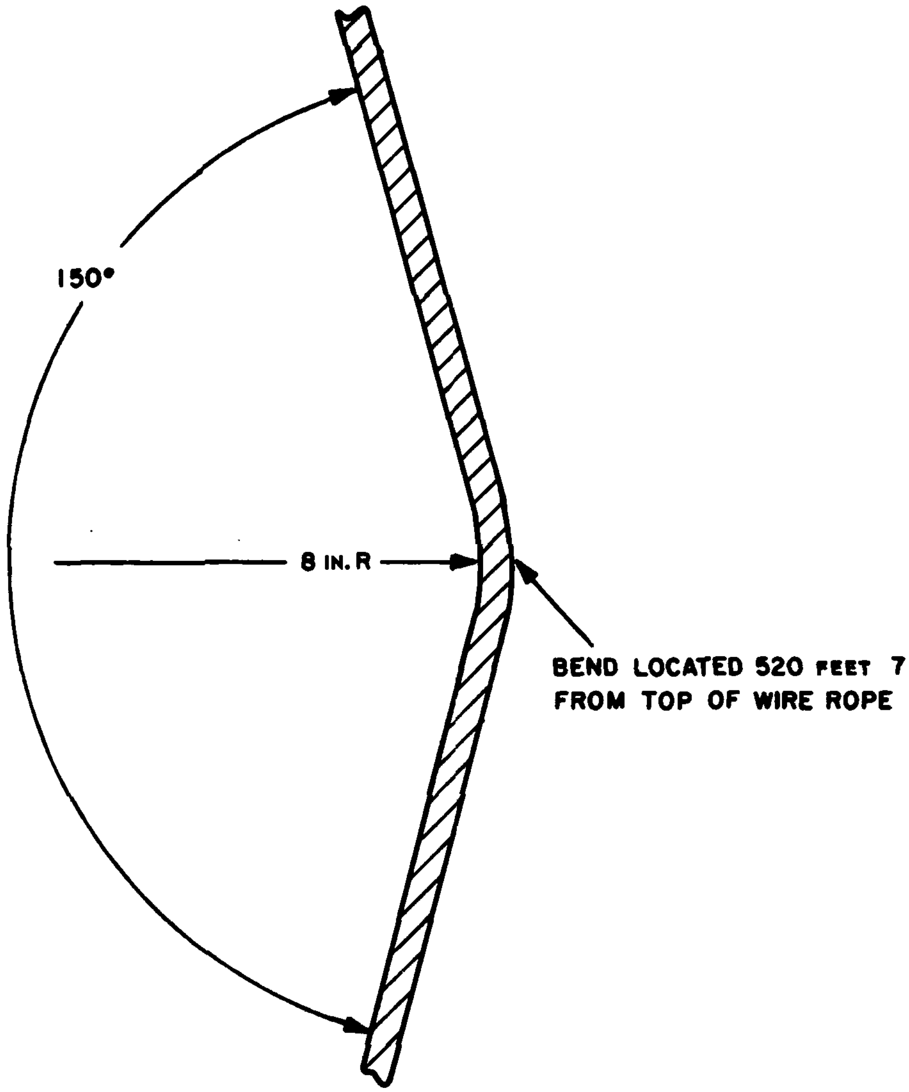


Fig. 3 - Permanent Bend In 3/4 in. Stainless Steel Rope. This permanent deformation (shown in a relaxed condition) initiated internal damage in the wire rope.

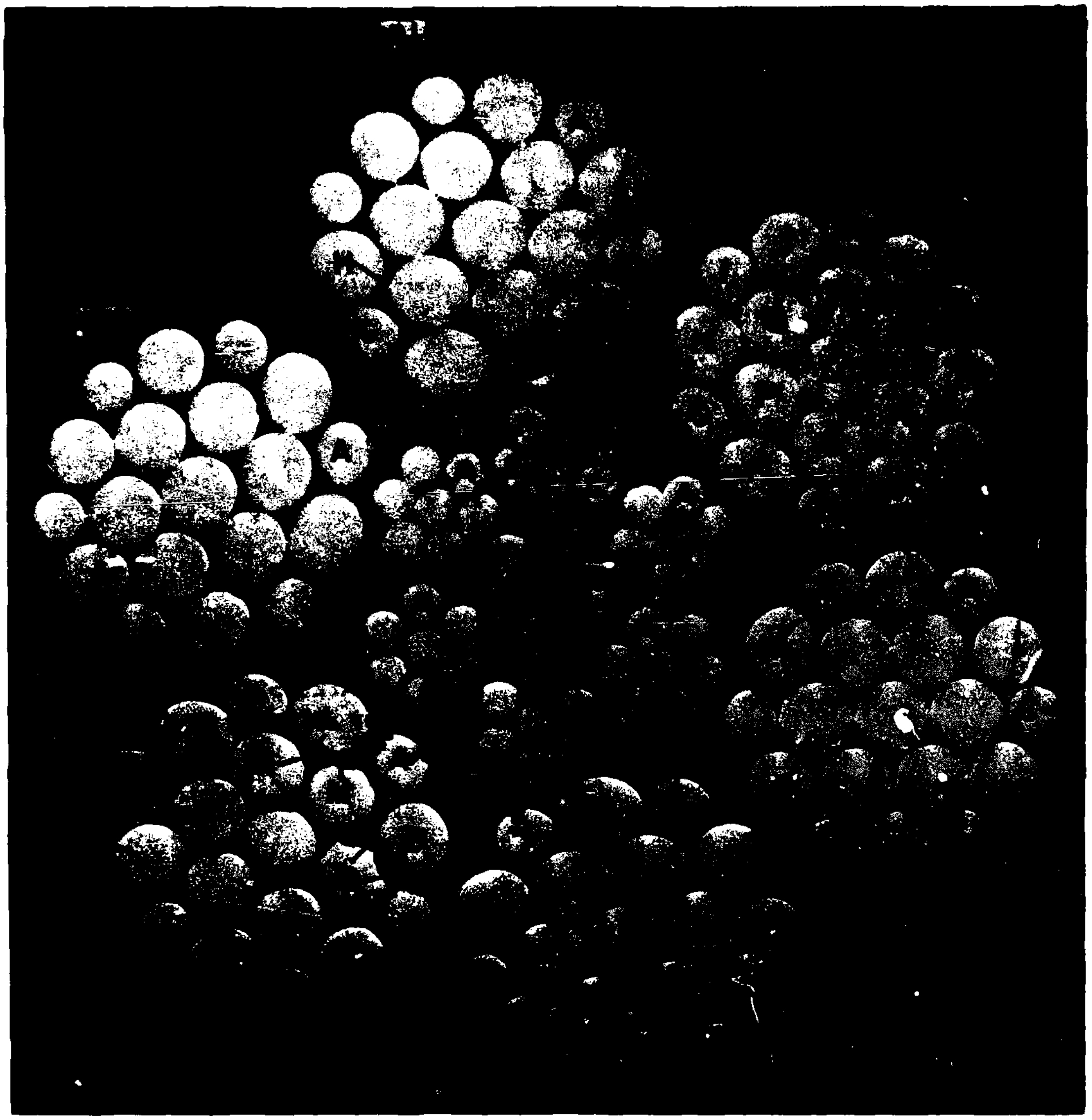


Fig. 4 - Wire And Strand Labels And Identification Of Major Rope Defects. Strand numbers and wire letters enable the location of defects within the rope construction. Cross-hatched wires within the IWRC identify the predominant location of complete wire breaks. This photograph indicates damage defects typical of those found at distances of 1010 feet and 1227 feet from the buoy end of the rope mooring. The average diameters of undamaged wires were as follows:

Outer Strand	13 wires .054 in. D.	IWRC Outer Strand	7 wires .032 in. D.
	6 wires .0415 in. D.	Center Strand	7 wires .036 in. D.

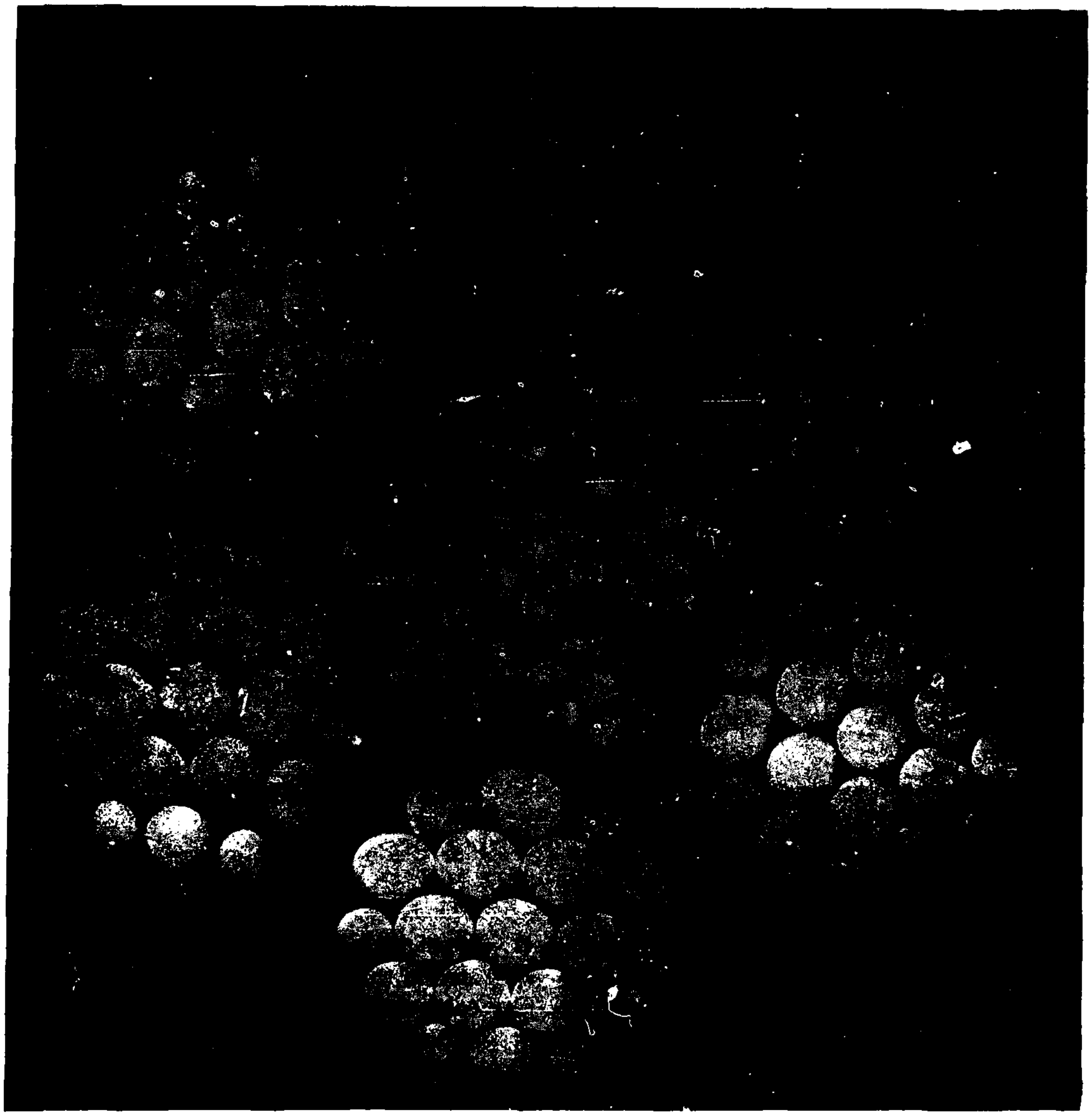
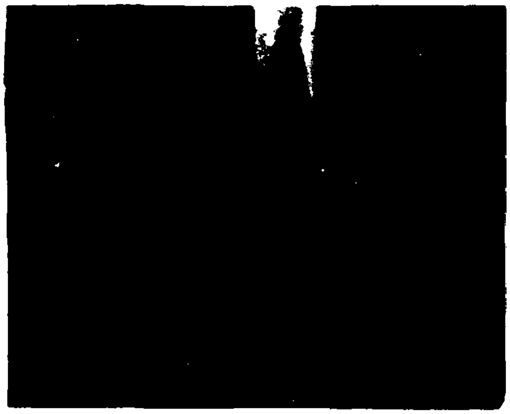
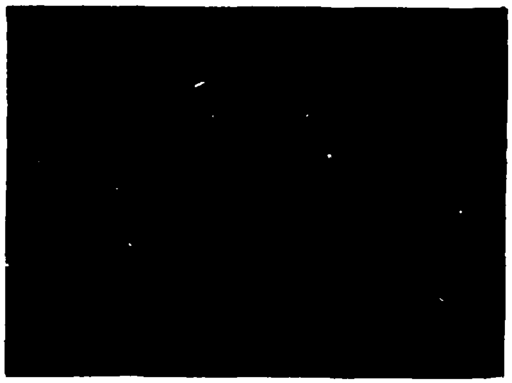


Fig. 5 - Photograph Of Relatively Undamaged Portion Of The Rope. This view is typical of the light extent of damage found at distances of approximately 13, 98, 1000, 1090 and 1103 feet from the buoy end of the mooring.



A - Medium scrape in outer wire of the rope
(10 X magnification)

B - Medium wire marks in outer-strand wire where it makes contact with the IWRC
(30 X magnification)



C - Light wire marks on outer-strand wire where it makes contact with adjacent inner wires
(30 X magnification)

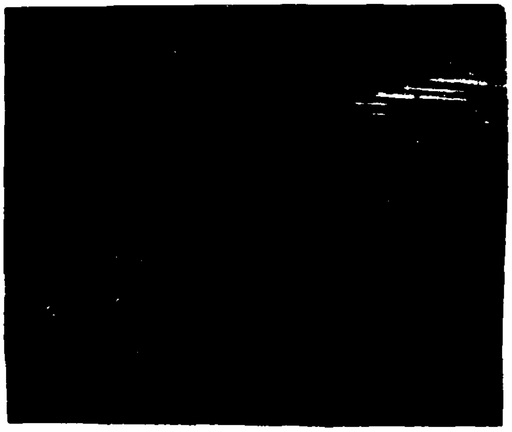
Fig. 6 - Mechanical Damage Defects. Defects of this magnitude were predominantly located at an approximate distance of 1010 and 1227 feet from the top of the mooring.

A - Two breaks are shown, one in the center wire of an outer IWRC strand and the other in an outer wire of the same strand.
(30 X magnification)

B - Center wire break in outer IWRC strand.
(30 X magnification)

C - Heavy tunneling, inner side of outer strand wire.
(30 X magnification)

Fig. 7 - Wire Breaks And Corrosive Tunneling. Wire breaks occurred only in wires in the IWRC; tunneling was predominant in wires of the outer strands. Both defects were located at distances of approximately 1010 and 1227 feet from the buoy end of the mooring.



A - Medium etch and burnish marks due to contact with adjacent wire in outer strand. (30 X magnification)

B - Heavy pits - inner side of outer strand wire. (30 X magnification)

C - Heavy striation, inner side of outer strand wire. (30 X magnification)

Fig. 8 - Corrosion Defects. Corrosion defects of this magnitude were present in some quantity at locations adjacent to the bend in the rope (520 feet from the buoy end of the mooring). These defects were located in very large numbers at a distance of approximately 1010 and 1227 feet from the buoy end of the wire rope mooring.

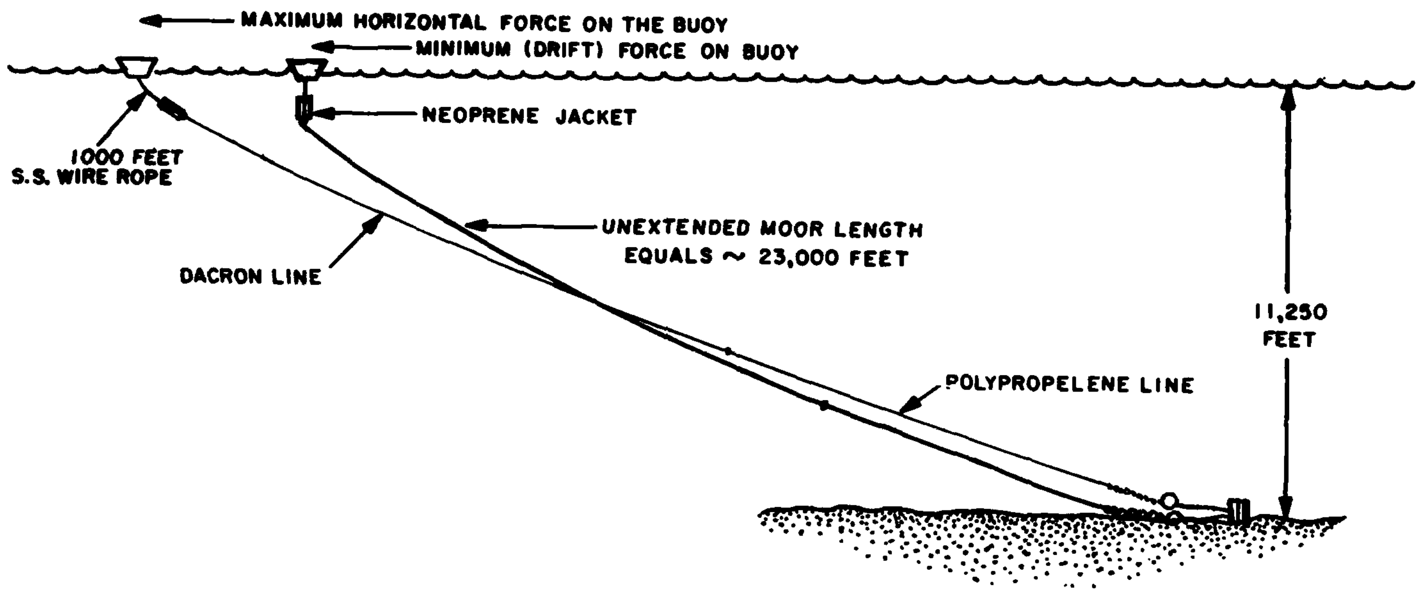


Fig. 9 - Forces And Motions In The General NOMAD System. The relative position of mooring components is shown for a maximum and a minimum horzontal force on the buoy. The sketch is also applicable to the particular NOMAD system under study.

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13. ABSTRACT

Damage analysis of samples from a 304 stainless steel rope was conducted to determine the extent and origin of damage mechanism defects and to measure their acumulated effect upon mooring line break strength. The rope was located in the upper portion of the NOMAD buoy mooring line and had been subjected to 34 months of continuous immersion in the Gulf of Mexico. The primary objective of this initial study was to supply corrective information leading towards an extension of service life.

Damage defects of mechanical and electrochemical origin were identified and located in the 1250-foot length of wire rope mooring. A study of these defects revealed a specific pattern of degradation. Dominant centers of damage were associated with a wire rope deformation-bend and with a "protective" neoprene jacket cover. In each case the initiating damage mechanism was identified as an abnormal mechanical motion which removed the protective coatings afforded by lubricant and cathodic protection. Subsequent corrosion of the stainless steel generated an abrasive sediment in the lubricant to promote a self-supporting degradation process. The wire rope retained 88% of its initial break strength. Elimination of the causes that initiated abnormal mechanical motion would increase this retained strength to 96%.

This study indicates the need to properly use post-service damage analysis in optimization of buoy system design. A complete understanding of usage effects in terms of failure/reliability will depend upon continued damage analysis during several protype installations.

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Buoy system design						
Marine corrosion studies						
Serviced wire rope break strength						
Extension of wire rope service life						